This lecture will present mainly water tube boiler types, categorized by their combustion process and application.

Boilers for solid fuels

Combustion technologies for industrial and district heating systems

Combustion systems of a nominal thermal capacity exceeding 100kW are involved. These furnaces are generally equipped with mechanical or pneumatic fuel-feeding systems. Manual fuel-feeding is no longer customary due to high personnel costs and strict emission limits. Moreover, modem industrial combustion plants are equipped with process control systems supporting full automatic system operation. In principle, the following combustion technologies can be distinguished:

- fixed bed combustion
- fluidized bed combustion and
- pulverized fuel combustion.

The basic principles of these three technologies are shown in Figure.

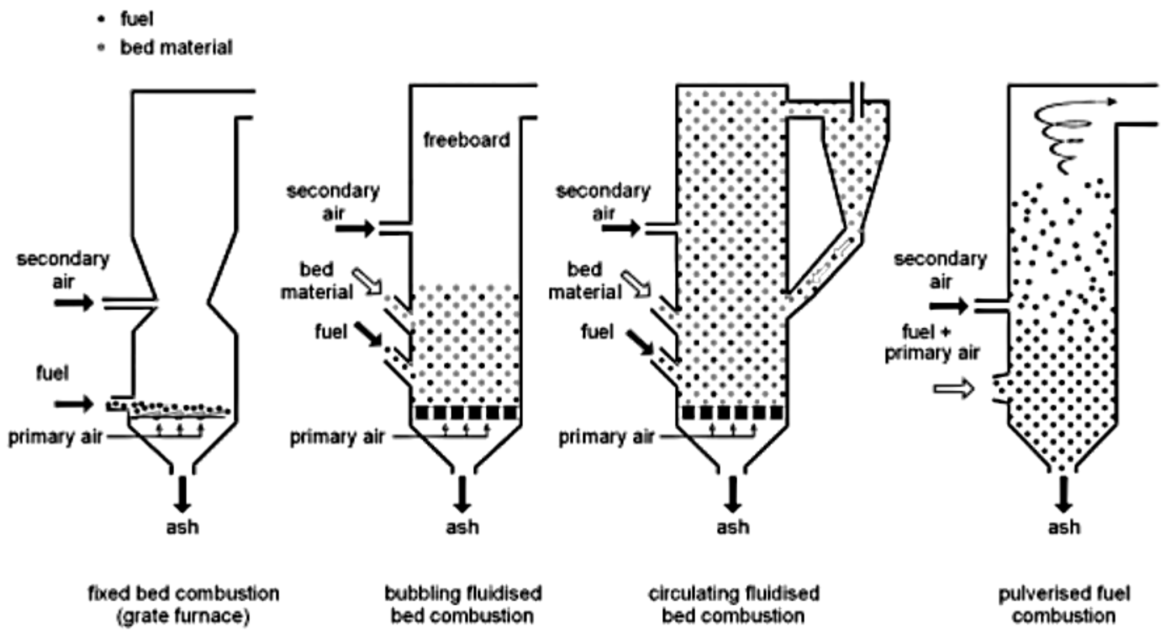


Figure 1: Principal combustion technologies for solid fuels.

Fixed bed combustion systems include grate furnaces and underfeed stokers. Primary air passes through a fixed bed, in which drying, gasification and charcoal combustion take place. The combustible gases produced are burned after secondary air addition has taken place, usually in a combustion zone separated from the fuel bed.
Within a fluidized bed furnace, fuel is burned in a self-mixing suspension of gas and solid-bed material into which combustion air enters from below. Depending on the fluidization velocity, bubbling fluidized bed (BFB) and circulating fluidized bed (CFB) combustion can be distinguished.
Pulverized fuel (PF) combustion is suitable for fuels available as small particles (average diameter smaller than 0,2 mm). A mixture of fuel and primary combustion air is injected into the combustion chamber Combustion takes place while the fuel is in suspension and gas burnout is achieved after secondary air addition.
Variations of these technologies are available Examples are combustion systems with spreader stokers and cyclone burners.

Grate furnace boilers

Grate firing has been the most commonly used firing method for combusting solid fuels in small and medium-sized furnaces (15 kW – 30 MW) since the beginning of the industrialization. New furnace technology (especially fluidized bed technology) has practically superseded the use of grate furnaces in unit sizes over 5 MW. Waste and bio-fuels are usually burned in grate furnaces. Since solid fuels are very different there are also many types of grate furnaces. The principle of grate firing is still very similar for all grate furnaces (except for household furnaces). Combustion of solid fuel in a grate furnace, which can be seen in Figure 2, follows the same phases as any combustion method:

- Removal of moisture - brown part
- Pyrolysis (thermal decomposition) and combustion of volatile matter - yellow part
- Combustion of char - red part

When considering a single fuel particle, these phases occur in sequence. When considering a furnace we have naturally particles in different phases at the same time in different parts of the furnace.

The grate furnace is made up a grate that can be horizontal or sloping (Figure 3). The grate can consist of a conveyor chain that transports the fuel forward. Alternatively some parts of the grate can be mechanically movable or the whole grate can be fixed. In the later case the fuel is transported by its own weight (sloping grate). The fuel is supplied in the furnace from the hopper and moved forward (horizontal grate) or downward (sloping grate) sequentially within the furnace. The primary combustion air is supplied from underneath the fire bed, by which the air makes efficient contact with the fuel, when blowing through the bed, to dry, ignite and burn it. The secondary (and sometimes tertiary) combustion air is supplied above the bed, in order to burn combustible gases that have been released from the bed.

The fuel is subjected to self-sustained burning in the furnace and is discharged as ash. The ash can has a relatively high content of combustible matter.

The grates in large-capacity plants are movable:

- traveling - consists of a set of hinged grate bars that are configured as a conveyor belt
- reciprocating
- rocking
- vibrating
- underfeed (retort)
- rotating

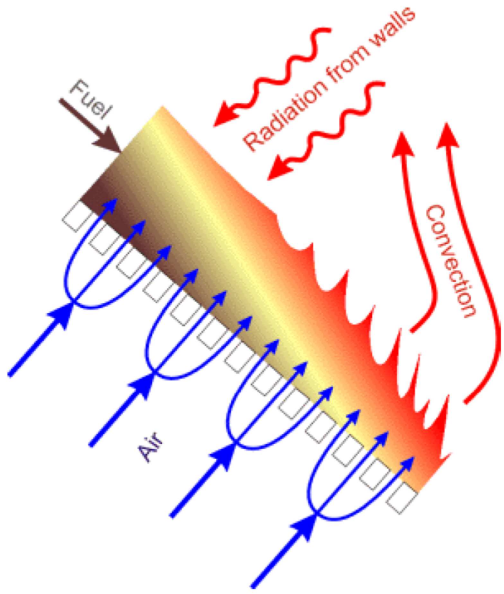


Figure 2: Drawing of the combustion process in a sloping grate furnace.

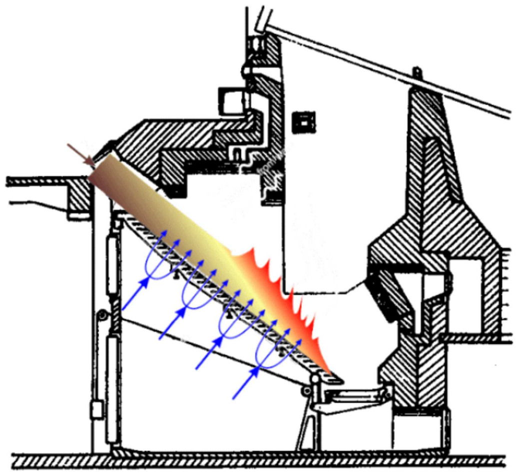


Figure 3: Sloped grate furnace.

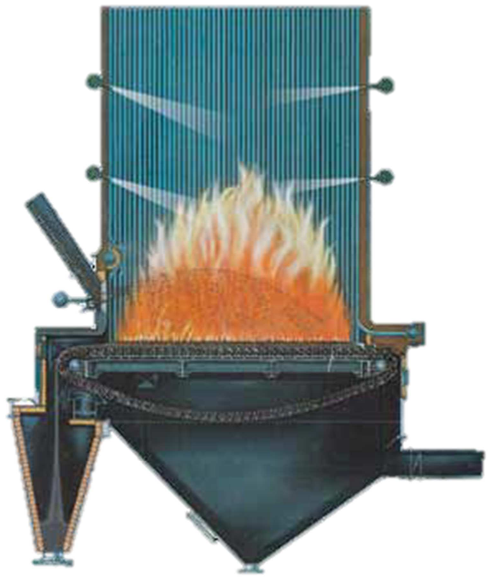


Figure 4: Traveling grate furnace.

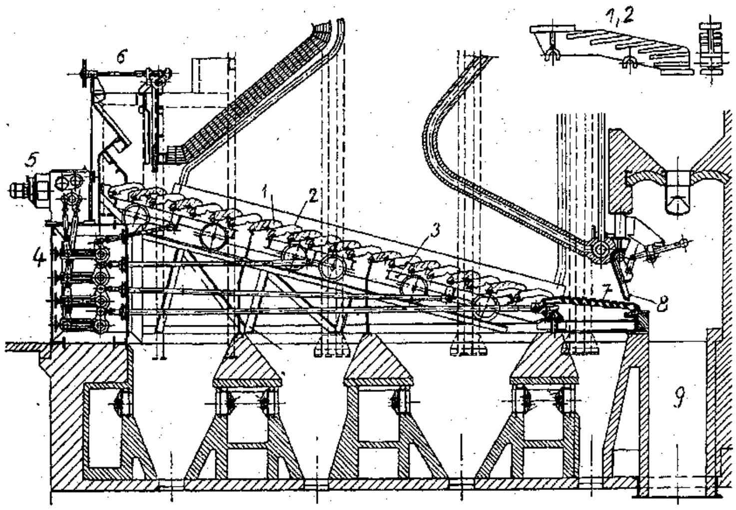


Figure 5: Reciprocating grate.

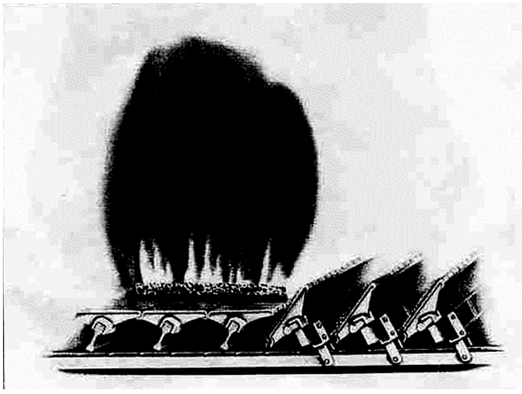


Figure 6: Rocking grate.

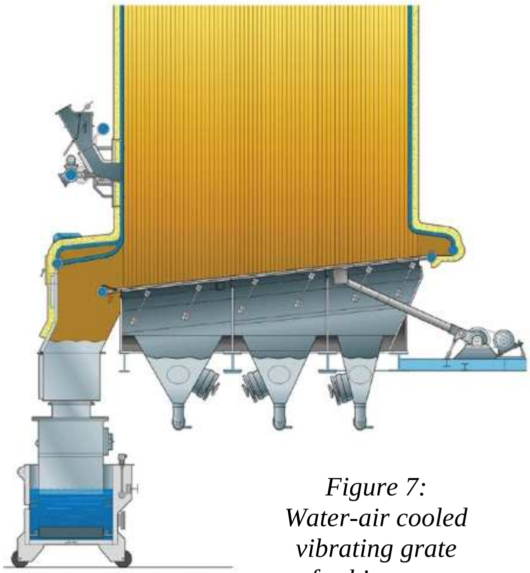


Figure 7: Water-air cooled vibrating grate for biomass.

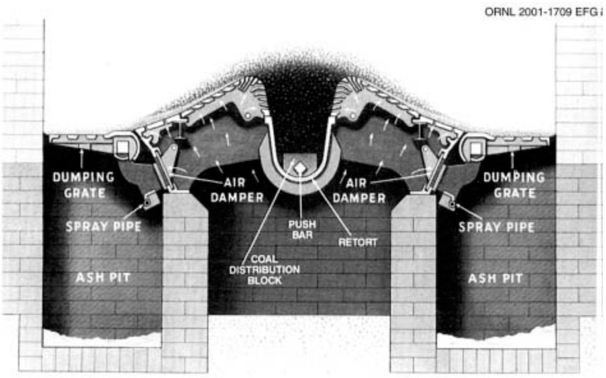


Figure 8: Underfeed grate.

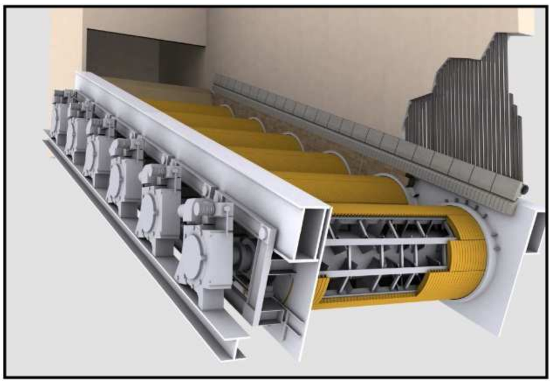


Figure 9: Rotating grate.

Pulverized coal fired (PCF) boilers

Coal-fired water tube boiler systems generate approximately 38% of the electric power production worldwide and will continue to be major contributors in the future. Pulverized coal fired boilers, which are the most popular utility boilers today, have a high efficiency but a costly SO_x and NO_x control. Almost any kind of coal can be reduced to powder and burned like a gas in a PCF-boiler. The PCF technology has enabled the increase of boiler unit size from 100 MW in the 1950's to far over 1000 MW. New pulverized coal-fired systems routinely installed today generate power at net thermal cycle efficiencies ranging from 40 to 47% (higher heating value) while removing up to 97% of the combined, uncontrolled air pollution emissions (SO_x and NO_x).

Coal is a heterogeneous substance in terms of its organic and inorganic content. Since only organic particles can be combusted, the inorganic particles remain as ash and slag and increase the need for particle filters of the flue gas and the tear and wear of furnace tubes. In order to be able to remove ash the furnace easier, the bottom of the furnace is shaped like a 'V'.

Firing systems

PC firing system can be divided by form of solid refuses leaving furnace to slag-tap and dry bottom.

Slag-tap (wet bottom) firing system means that ash is melted to liquid glassy matter flowing out from the bottom of furnace. Cyclone firing system or U/double U firing system is commonly used in this case.

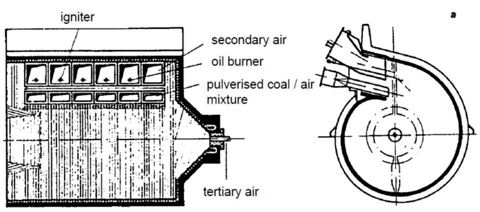
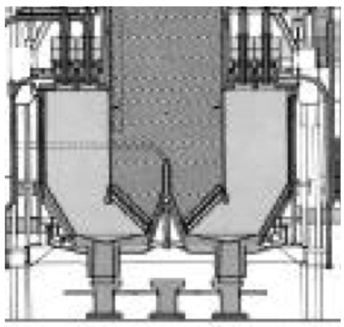
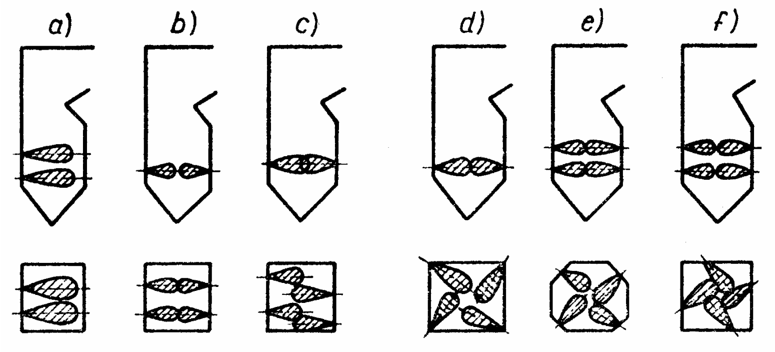


Figure 10: Cyclone



Double U furnace

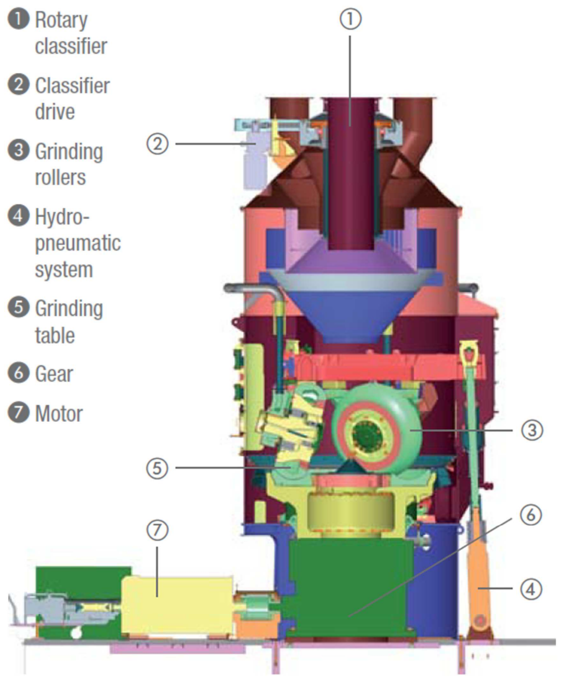
In **dry bottom firing system**, ash particles are melted on their surface only, stick together and create solid porous cinder leaving the furnace in smaller of bigger pieces. Burners arrangements suitable for dry bottom firing systems are front (a), opposed (b, c), corner (d) or tangential (e,f).



The pulverized coal is blown with part of the combustion air into the boiler plant through a series of burner nozzles. Secondary and tertiary air may also be added. Combustion takes place at temperatures from 1300-1700°C, depending largely on coal grade. Particle residence time in the boiler is typically 2 to 5 seconds, and the particles must be small enough for complete combustion to have taken place during this time. This system has many advantages such as ability to fire varying quality of coal, quick responses to changes in load, use of high pre-heat air temperatures etc.

Coal preparation

The coal must be ground (pulverised) to a fine powder, so that less than 2% is +300 micro metre (μm) and 70-75% is below 75 microns, for a bituminous coal. It should be noted that too fine a powder is wasteful of grinding mill power. On the other hand, too coarse a powder does not burn completely in the combustion chamber and results in higher unburnt losses. Grinding usually combines with coal drying to improve ignition and burning which has to be completed in very short time before coal particles leave combustion chamber (~ 2 sec.). Preheated air or hot flue gas extracted from top part of furnace is used for drying depending on coal moisture. Ball or roller mill and tubular mills with air drying are used for hard coal pulverizing. Fan mill with flue gas drying is suit for grinding of more soft and moist lignite.



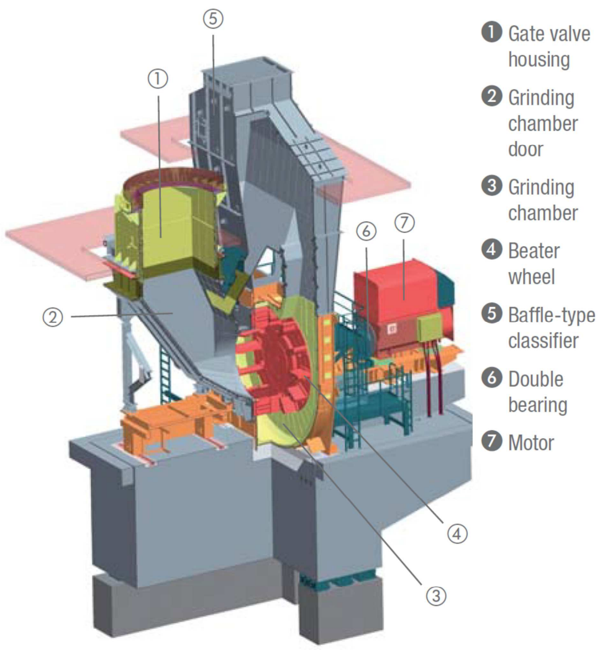


Figure 11: Roller mill for hard coal *Fan mill for moist lignite*

Burners

A burner is defined as a device or group of devices for the introduction of fuel and air into a furnace at the required velocities, turbulence, and concentration to maintain ignition and combustion of fuel within the furnace. Burners for gaseous or liquid fuels are less complex than those for PCF boilers because mixing of gas or atomizing liquid and combustion air is relatively simple compared dispersing solid fuel particles.

The ability of a burner to mix combustion air with fuel is a measure of its performance. Two basic types of burners for PC firing are used:

- **jet** with slow mixing of parallel fuel and air flows – suitable for lignite
- **swirl** with intensive turbulent mixing of fuel and air flows – suitable for hard coal

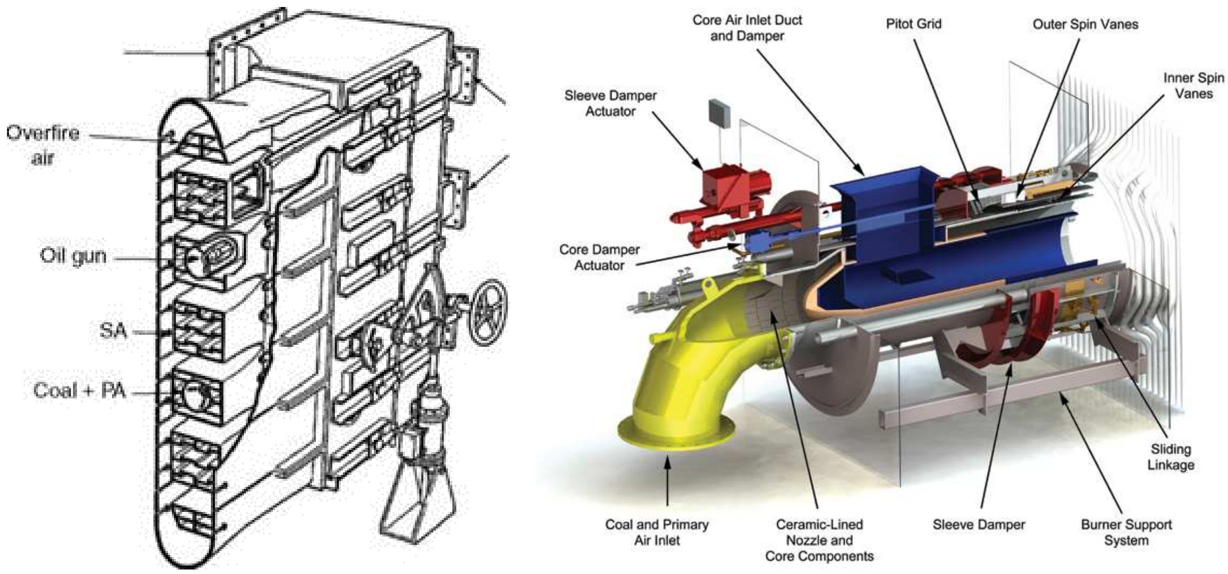


Figure 12: Jet burner for lignite Swirl low NOx burner for hard coal

The burners are engineered to liberate the maximum amount of heat from the fuel and limit the amount of pollutants such as CO and NOx that are released. Burners with these capabilities are now used routinely in boilers that must comply with mandated emission limitations.

Boiler shapes

Since the mid 19th century two pass boilers have been the preferred boiler design in Europe. The two pass boilers designed have been in the range from 80 MWe to 640 MWe.
The tower type design has number of advantages such as the reduced foot print, reduced weight of boiler pressure part, fully drainable pressure part, no extraction of fly ash and uniform flue gas temperature profile. The advantages are described more in detail below.

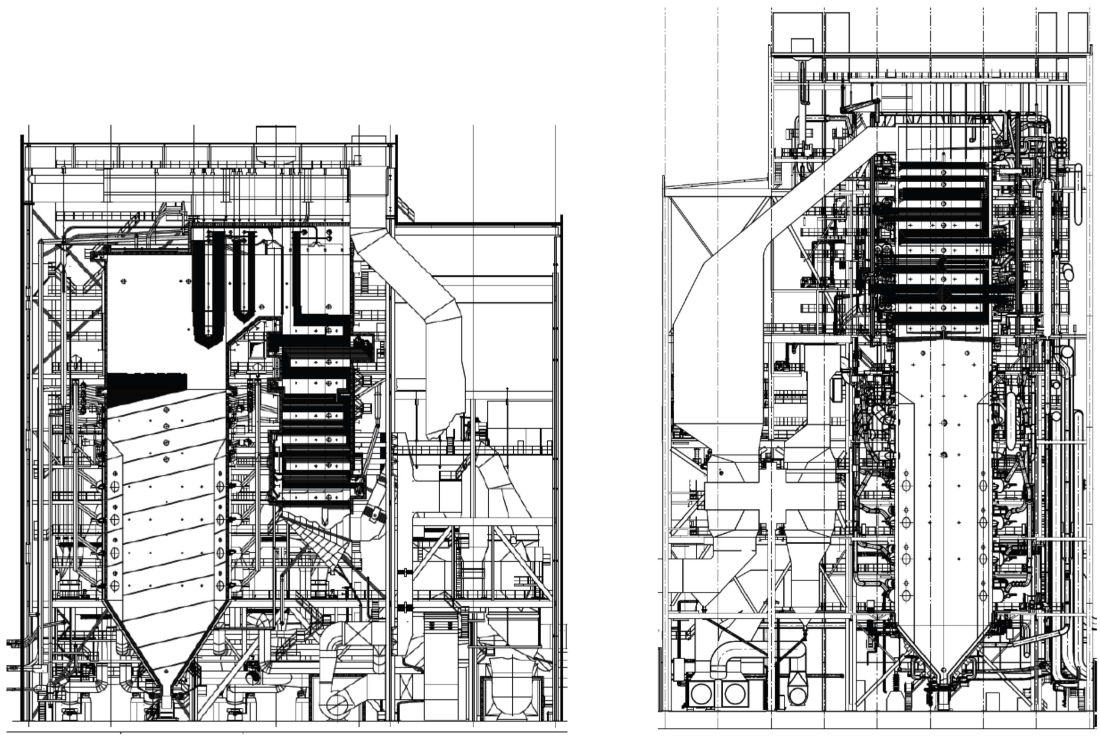


Figure 13: Two pass boiler Tower type boiler

The reduced foot print subsequently leads to a reduced boiler steel structure even through the total height is increased.
Since the heating surfaces of a tower type boiler are affected by a flue gas flow perpendicular to the banks, the heating surface will be fully effective as opposed to the two pass boiler where the heat absorption efficiency of

the hanging super heaters is reduced. Subsequently the weight of the pressure part for a tower type boiler will be reduced compared to a two pass boiler.
All heating surfaces are arranged horizontally resulting in a fully drainable pressure part. Especially during start up, condensate can be drained out, pipe lines heated up and the steam temperature increased faster. For short overhauls dry preservation can easily be used.
The advantages of the two pass boiler are the lower total height of the boiler and the easy erection of the boiler top including headers, heating surfaces and boiler ceiling. However the design of the boiler top of a two pass boiler is quite complicated. The boiler ceiling of the tower type is un-cooled. The boiler suspension is very simple and does not require any penthouse. In the light of a better performance in the total life time of more than 35 years some extra months for construction of the tower type boiler should be accepted.
The two pass boiler has some design limitations which are difficult to avoid. Temperature difference between first pass and vestibule / second pass membrane wall will often lead to crack after some years of operation. The tower type boiler has a very simple design of membrane walls and a smooth increase in temperature. An additional problem in the two pass boiler is when the flue gas is leaving the first pass and enters into the second pass, the particles of the flue gas will be concentrated close to the rear wall of the second pass and result in erosion of the super heater banks. Especially for high ash coal this will be a challenge and normally call for erosion shields.
The two pass boiler has some geometrical limitation which makes it difficult to optimize the boiler pressure part design. The pitch of the first hanging super heater banks SH-1 needs to have a mutual distance (400-800mm) to avoid blocking of slag. On the tower type boiler the first super heater banks SH-1which are typically arranged just above the final reheater can be designed with smaller pitch (100-200mm). The number of parallel tubes can be higher and subsequently the pressure loss will be smaller.

Tower type	Two pass
Uniform flue gas profile and reduced temperature peak in pressure part	Uneven flue gas flow profile and high ash concentration on second pass rear wall
Excellent RH temperature characteristic	Cold built in conditions for final RH
Effective heating surfaces, no ineffective (dead) areas	Partly in-effective heating surfaces
Reduced foot print, increased height	Reduced height, enlarged footprint
Low pressure loss due to high number of parallel tubes in super heater banks	Higher pressure loss due to limitation in heating surface design
Easy installation of SCR	Difficult installation of SCR and increased duct work
Smooth membrane wall temperature increase	Thermo stress and cracks in membrane wall between first pass and vestibule / second pass
No extraction of fly ash	Extraction of fly ash below ECO
Fully drainable super heaters, fast start up.	Risk of blocking the hanging super heaters by exfoliated magnetite.
Simple boiler suspension, penthouse not required	Complicated boiler suspension

Fluidized bed boilers

Fluidized bed combustion was not used for energy production until the 1970's, although it had been used before in many other industrial applications. Fluidized bed combustion has become very common during the last decades. One of the reasons is that a boiler using this type of combustion allows many different types of fuels, also lower quality fuels, to be used in the same boiler with high combustion efficiency. Furthermore, the combustion temperature in a fluidized bed boiler is low (~850 °C), which directly induce lower NOx emissions. Fluidized bed combustion also allows a cheap SOx reduction method by allowing injection of pulverized limestone directly into the furnace.

Principles

The principle of a fluidized bed boiler is based on a layer of ash, sand or any solid particles, where the fuel is introduced into and combusted. The combustion air blows through the layer from an opening in the bottom of the boiler. Depending on the velocity of the combustion air, the layer gets different types of fluid-like behavior, as listed and described in

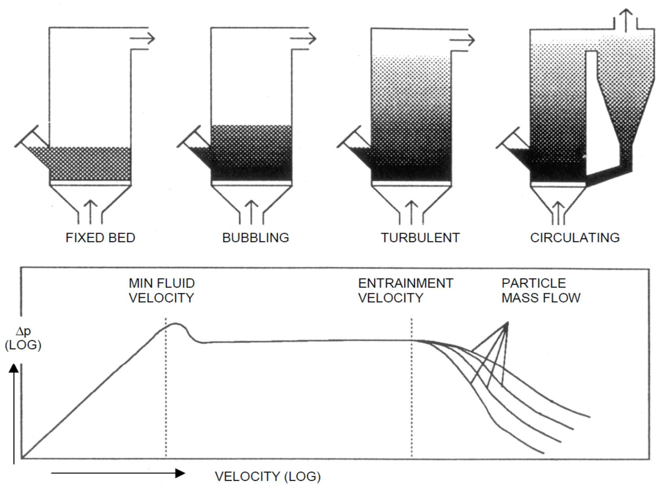


Figure 14: Regimes of fluidised bed systems.

Figure. This type of combustion has the following merits:

- Fuel flexibility; even low-grade coal such as sludge or refuse can be burned
- High combustion efficiency
- Low NOx emission
- Control of SOx emission by desulfurization during combustion; this is achieved by employing limestone as a bed material or injecting limestone into the bed.
- Wide range of acceptable fuel particle sizes; pulverizing the fuel is unnecessary
- Relatively small installation, because flue gas desulfurization and pulverizing facilities are not required

Main types

There are two main types of fluidized bed combustion boilers: Bubbling fluidized bed (BFB) and circulating fluidized bed (CFB) boilers.

In the bubbling type, because the velocity of the air is low, the medium particles are not carried above the bed. The combustion in this type of boiler is generated in the bed. Figure shows an example of a BFB boiler schematic. The CFB mode of fluidization is characterized by a high slip velocity between the gas and solids and by intensive solids mixing. High slip velocity between the gas and solids, encourages high mass transfer rates that enhance the rates of the oxidation (combustion) and desulfurization reactions, critical to the application of CFB's to power generation. The intensive solids' mixing insures adequate mixing of fuel and combustion products with combustion air and flue gas emissions reduction reagents. In the circulating type, the velocity of air is high, so the medium sized particles are carried out of the combustor. The carried particles are captured by a cyclone installed in the outlet of combustor. Combustion is generated in the whole combustor with intensive movement of particles. Particles are continuously captured by the cyclone and sent back to the bottom part of the combustor to combust unburned particles. This contributes to full combustion.

The CFB boiler has the following advantages over the BFB Boiler:

- Higher combustion efficiency
- Lower consumption of limestone as a bed material
- Lower NOx emission
- Quicker response to load changes

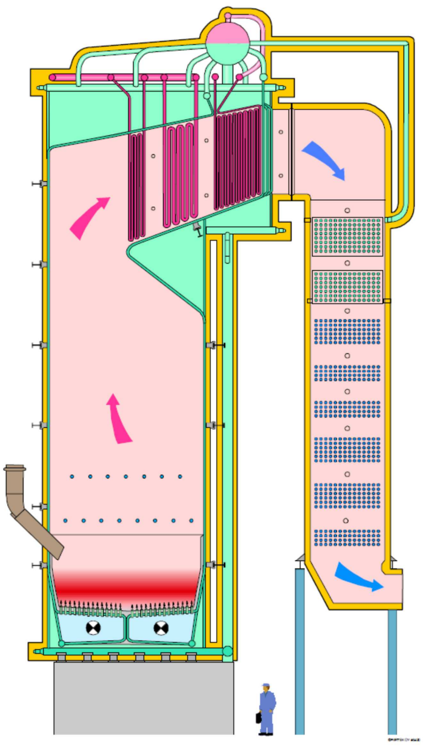


Figure 15: BFB boiler

BFB boilers have typically a power output lower than 100 MW and CFB boilers range from 100 MW to 500 MW. In recent years, many CFB boilers have been installed because of the need for highly efficient, environmental-friendly facilities.

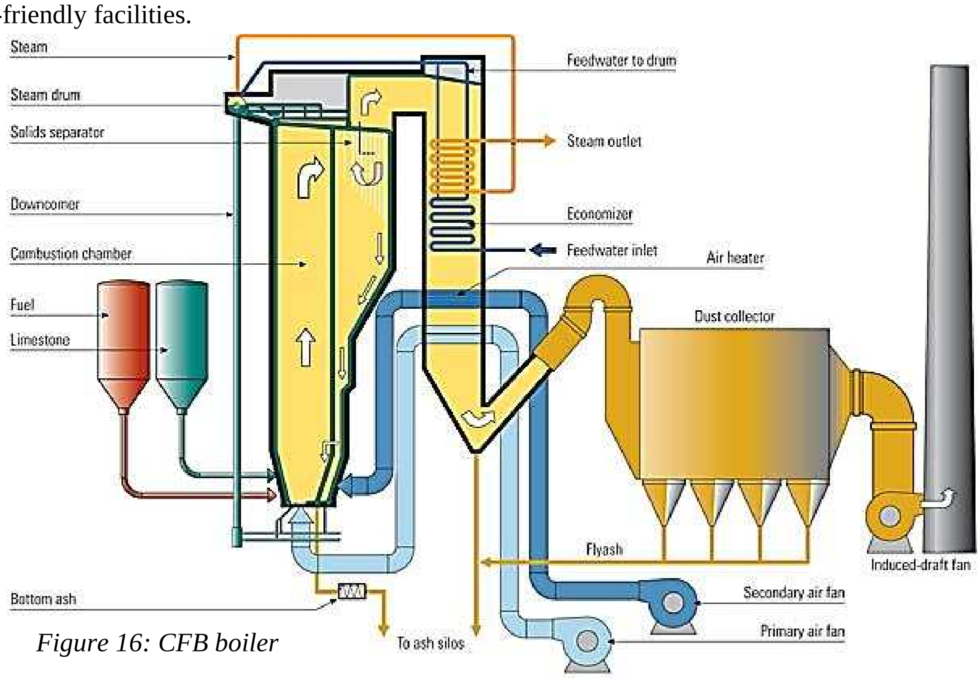


Figure 16: CFB boiler

Oil and gas fired boilers

Oil and natural gas have some common properties: Both contain practically no moisture or ash and both produce the same amount of flue gas when combusted. They also burn in a gaseous condition with almost a homogenous flame and can therefore be burnt in similar burners with very little air excess. Thus, oil and gas can be combusted in similar types of boilers. The radiation differences in the flue gases of oil and gas are too high in order to use both fuels in the same boiler. Combusting oil and gas with the same burner can cause flue gas temperature differences up to 100°C.

The construction of an oil and gas boiler is similar to a PCF-boiler, with the exception of the bottom of the furnace, which can be horizontal thanks to the low ash content of oil and gas. Horizontal wall firing (all burners attached to the front wall) is the most affordable alternative for oil and gas burners.

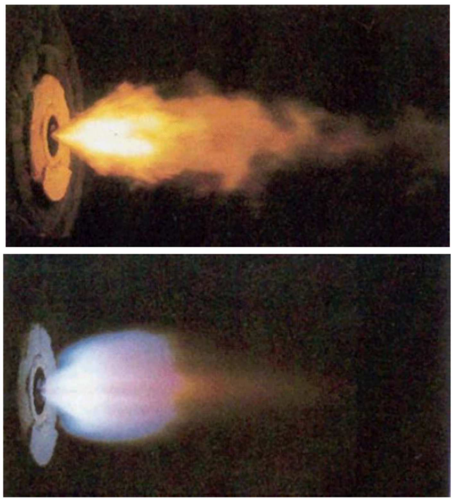
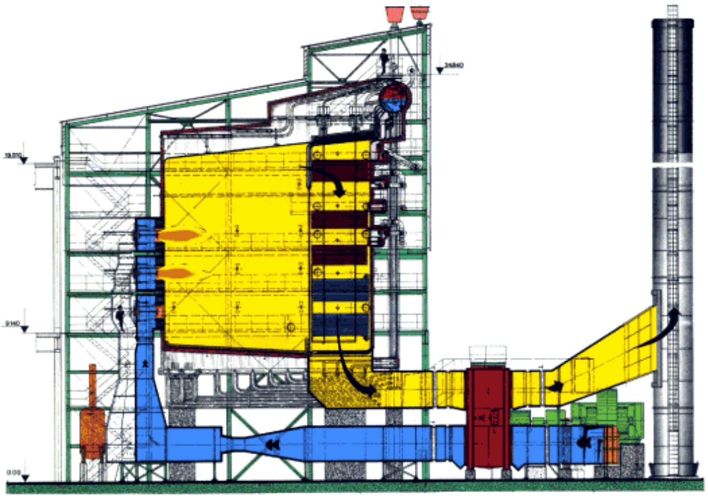


Figure 17: Oil flame / gas flame



Oil or Gas Boiler with horizontal wall firing

Heat recovery steam generators (HRSG)

As the name implies, heat recovery steam generators (HRSGs) are boilers where heat, generated in different processes, is recovered and used to generate steam or boil water. The main purpose of these boilers are to cool down flue gases produced by metallurgical or chemical processes, so that the flue gases can be either further processed or released without causing harm. The steam generated is only a useful by-product. Therefore extra burners are seldom used in ordinary HRSGs. HRSGs are usually a link in a long process chain, which puts extremely high demands on the reliability and adaptability of these boilers. Already a small leakage can cause the loss of the production for a week. Problems occurring in these boilers are more diverse and more difficult to control than problems in an ordinary direct heated boiler. Figure shows an example of a HRSG with horizontal layout.

HRSGs in CCGT plants

Gas turbines are nowadays commonly used in generating electricity in power plants. The temperature of the flue gases from gas turbines is usually over 400°C, which means that a lot of heat would be released into the environment and the gas turbine plant works on a low efficiency. The efficiency of the power plant can be improved significantly by connecting a heat recovery boiler (HRSG) to it, which uses the heat in the flue gases to generate steam. This type of combination power generation processes is called a combined cycle. Figure shows an example of a HRSG for CCGT plant with horizontal layout.

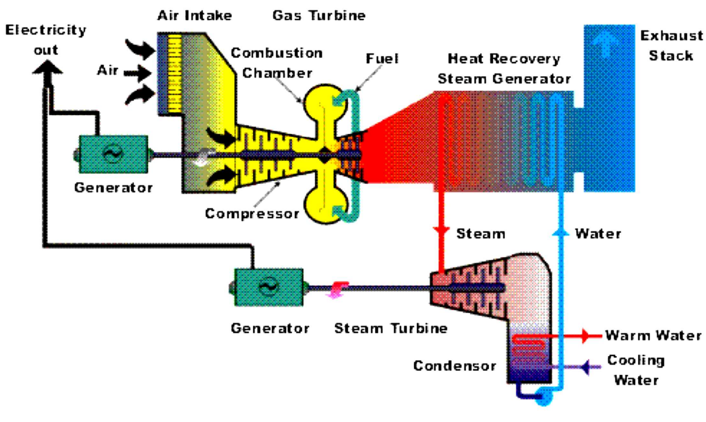
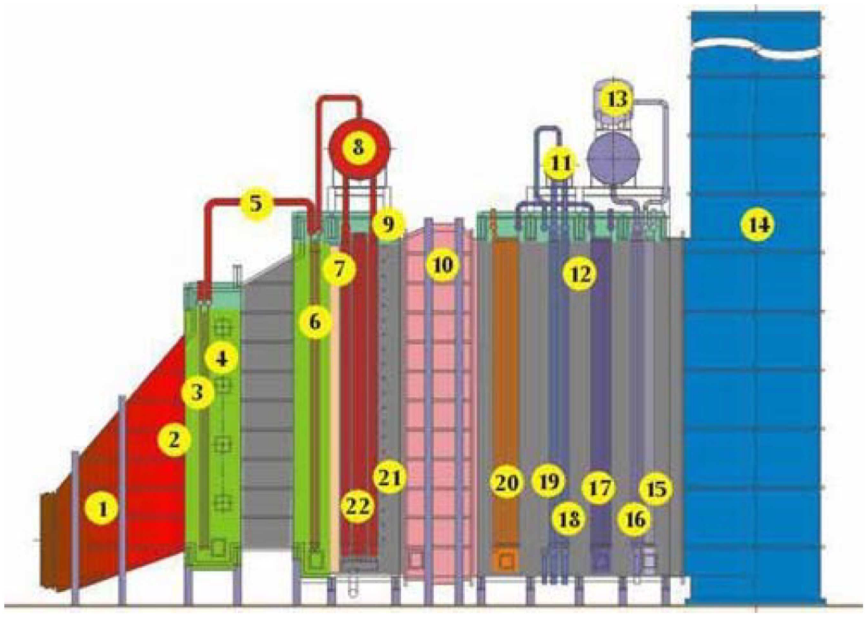


Figure 18: CCGT plant

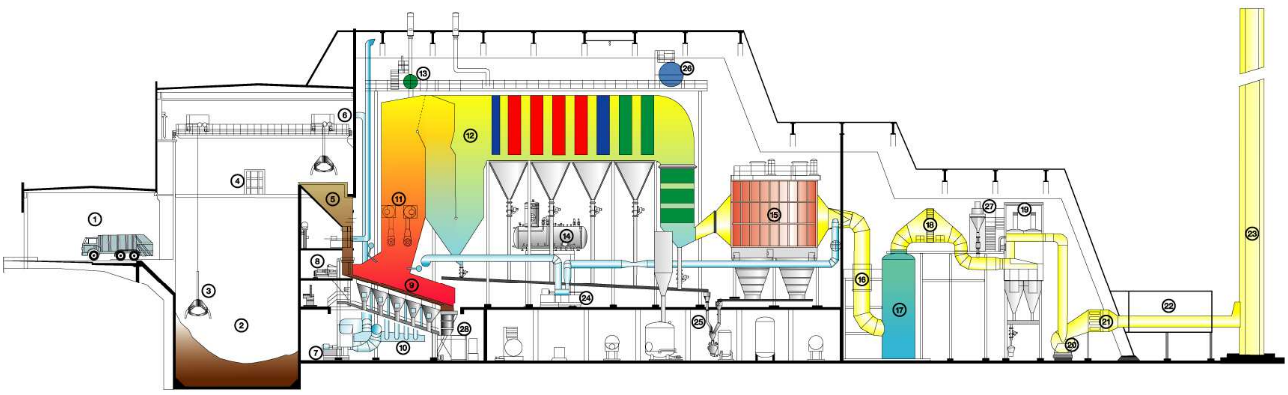


1 Inlet Duct
2 Distribution grid
3 HP Superheater 1
4 Burner
5 Split Superheater
6 HP Superheater 2
7 CO Catalyst
8 HP Steam Drum
9 Top Supports
10 SCR Catalyst
11 LP Steam Drum
12 HRSG Casing
13 Deareator
14 Stack
15 Preheater
16 DA Evaporator
17 HP/IP Economizer
18 IP Evaporator
19 IP Superheater
20 HP Economizer
21 Ammonia Injection Grid
22 HP Evaporator

Figure 19: Horizontal HRSG

Refuse boilers

The standard refuse (or waste) recovery boiler incinerates solid or liquid waste products. The combustion of waste differs radically compared to other fuels mostly due to the varying properties of waste. Also, the goal when combusting waste is not to produce energy, but to reduce the volume and weight of the waste and to make it more inert before dumping it on a refuse tip. Waste is burned in many ways, but the main method is to combust it in a grate boiler with a mechanical grate. Other ways to burn waste is to use a fixed grate furnace, a fluidized bed for sludge or rotary kilns for chemical and problematic waste. Waste is usually “mass burned”, i.e. it is burned in the shape it was delivered with minimal preparation and separation. The main preparation processes are grinding and crushing of the waste and removal of large objects. Waste has to be thoroughly combusted, so that harmful and toxic components are degraded and dissolved.
Waste can be refined into fuel, by separating as much of the inert and inorganic material as possible. This is called refuse derived fuel (RDF) and can be used as the primary fuel in fluidized bed boilers or burned as a secondary fuel with other fuels. RDF is becoming more common nowadays.



1 Truck Unloading Area
2 Waste Storage Pit
3 Overhead Crane
4 Crane Operator Pulpit
5 Feed Hopper
6 Primary Air Intake
7 Primary Air Fan
8 Ram Feeder
9 Incineration Grate
10 Primary Air Distribution
11 Auxiliary Burners
12 Heat Recovery Boiler
13 Boiler Drum
14 Feedwater Tank/Dearator
15 Electrostatic Precipitator
16 Quench
17 Wet Scrubber
18 Steam-to-gas heat Exchanger
19 Baghouse
20 Induced Draft Fan
21 Silencer
22 Emission Monitoring
23 Stack
24 Recirculated Flue Gas Fan
25 Ash Removal System
26 Emergency Water Tank
27 Adsorbent Metering Station
28 Deslagger

vonRoll INOVA

Figure 20: Municipal solid waste incineration plant